Measurement of four-alpha decays near the four-alpha threshold energy in ^{16}O

ITOH Masatoshi, KARASUDANI Kohei

Cyclotron and Radioisotope Center (CYRIC),
Tohoku University

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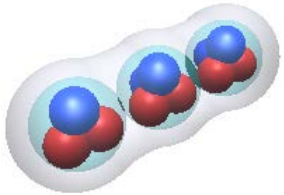
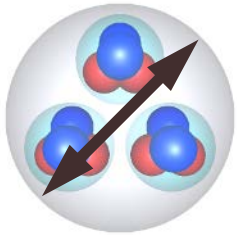
Introduction: Alpha gas-like structure

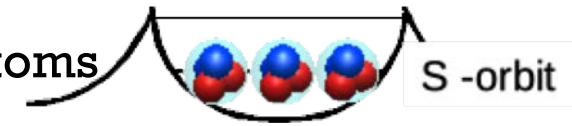


- Hoyle state: 0_2^+ state at 7.65 MeV in ^{12}C
  - Discovered in the β-decay of ^{12}B
    C.W.Cook, W.A.Fowler, C.C.Lauritsen, and T.Lauritsen, Phys.Rev. 107 (1957) 508
  - Difficult to be explained in the shell model
  - Linear 3α chain (Morinaga, Phys.Rev. 101 (1956) 254)
  - Loosely coupled 3α gas-like structure
    3α-OCM: H.Horiuchi, PTP51(1975)1266,
    3α-GCM:Uegaki et al, PTP57(1977)1262,
    3α-RGM: Kamimura, NPA351(1981)456.



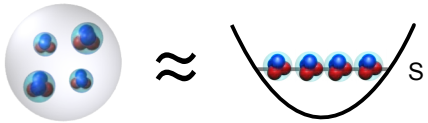
Large Radius with
a dilute density

- Alpha Cluster Condensation in ^{12}C and ^{16}O
  A.Tohsaki, H.Horiuchi, P.Schuck, and G.Ropke, Phys.Rev.Lett.87(2001)192501
  - α gas-like structure
    → similar to Bose-Einstein condensation of bosonic atoms
  - All α clusters enter into the same lowest S-wave orbit

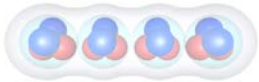


4α gas-like structures in ^{16}O

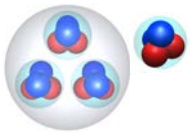
0^+ state at 15.1 MeV: α condensate state
Y.Funaki et al, Phys.Rev.Lett. 101 (2008) 082502

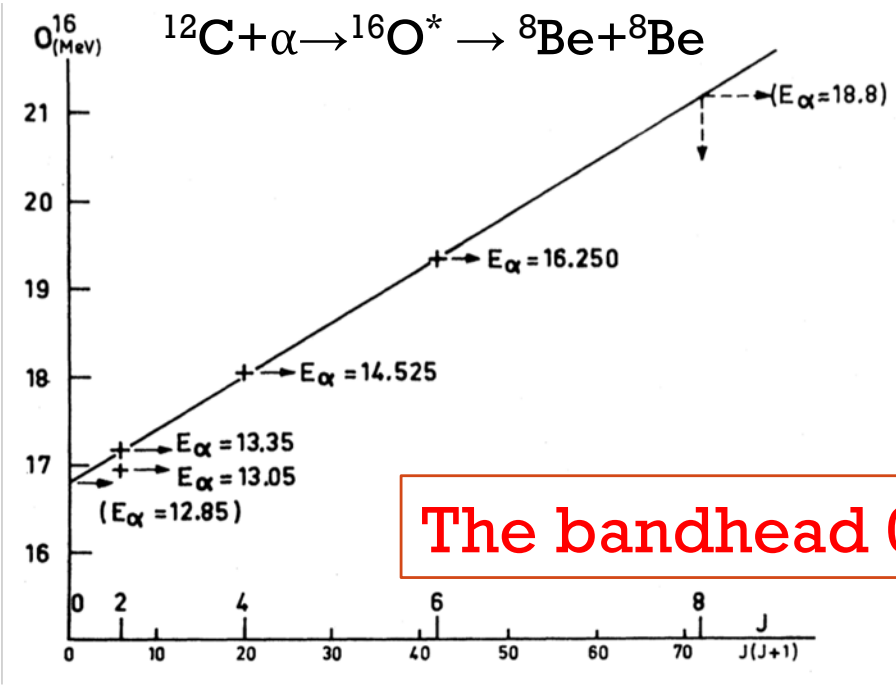


- Linear chain structure

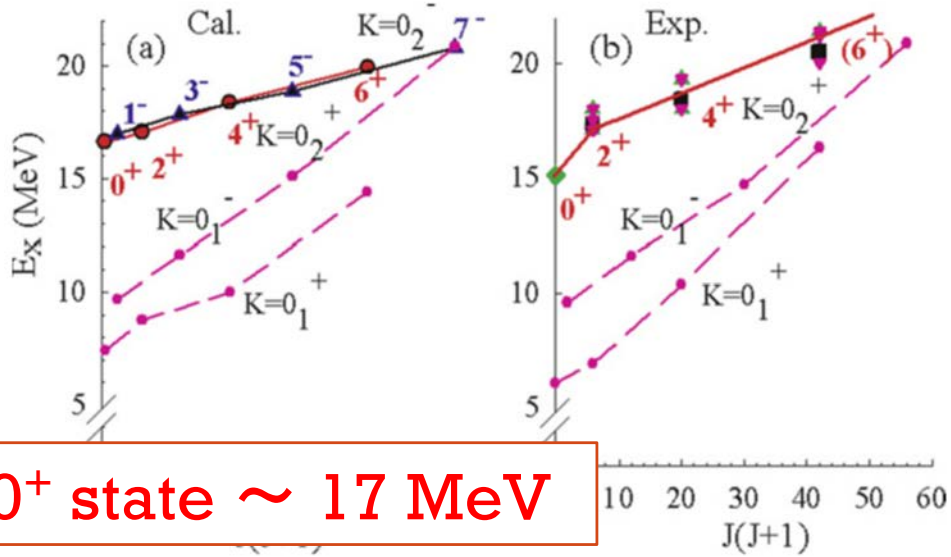


- Hoyle + α cluster





P.Chevallier,M.W.Sachs,Phys.Rev.160(1967)827

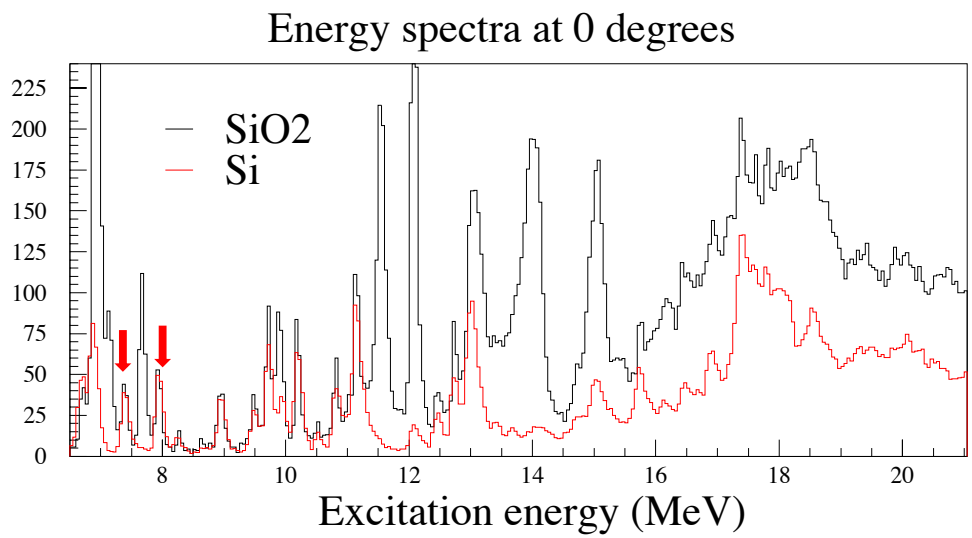


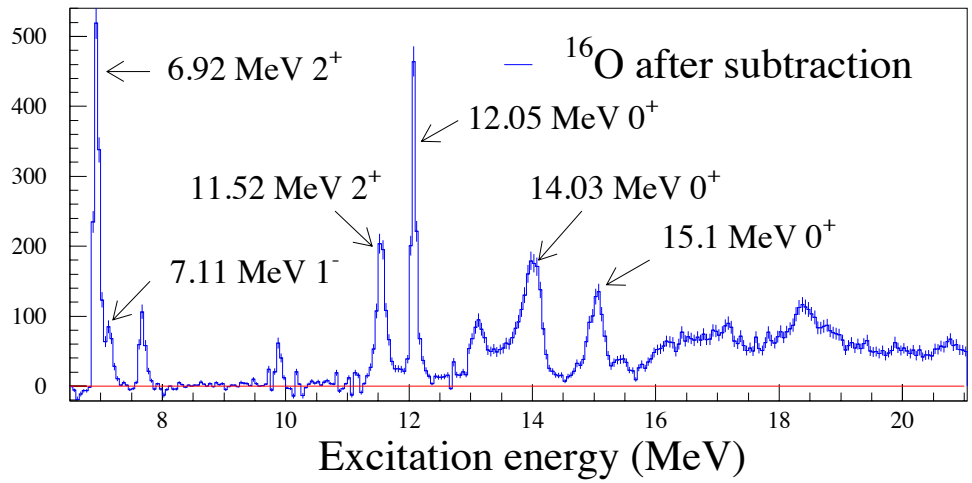
The bandhead 0^+ state ~ 17 MeV

S.Ohkubo,Y.Hirabayashi,
Phys.Lett.B684(2010)127

The $^{16}O(\alpha,\alpha')$ experiment at E_α = 386 MeV

- The (α,α') experiment at E_α = 386 MeV in RCNP
- SiO_2 2.0mg/cm^2
- Si 2.2mg/cm^2
- Thickness of Si in SiO_2 is normalized by 7.42 MeV 2^+ and 7.93 MeV 2^+ states in ^{28}Si.

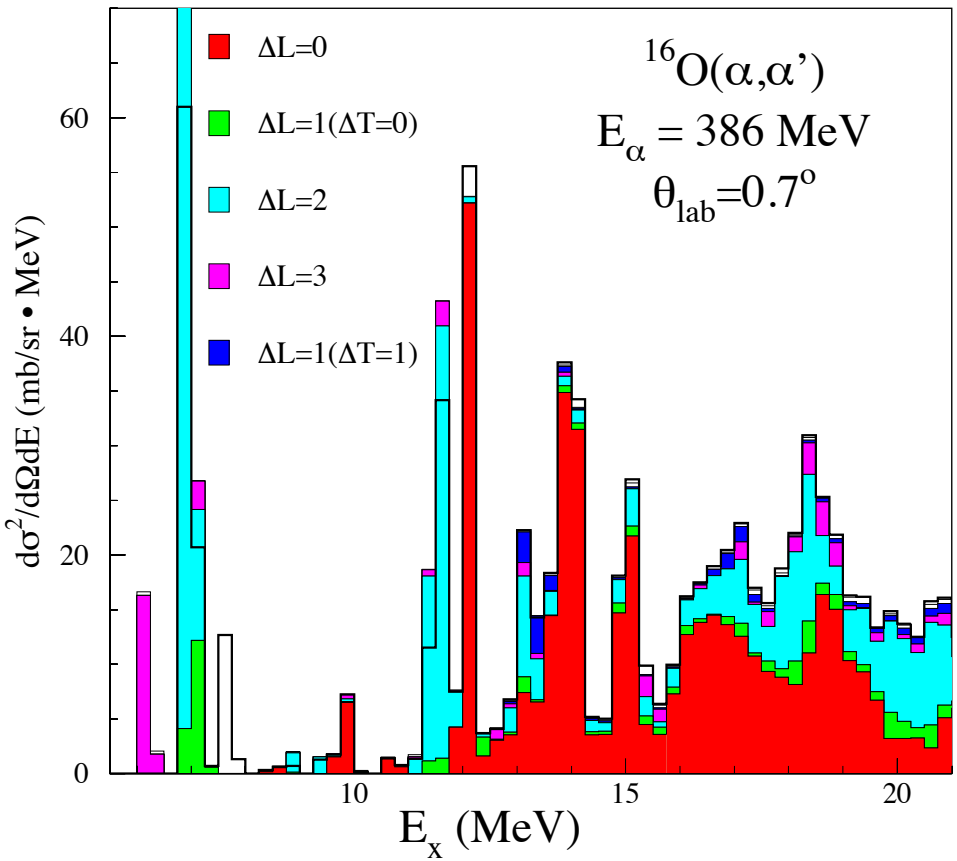


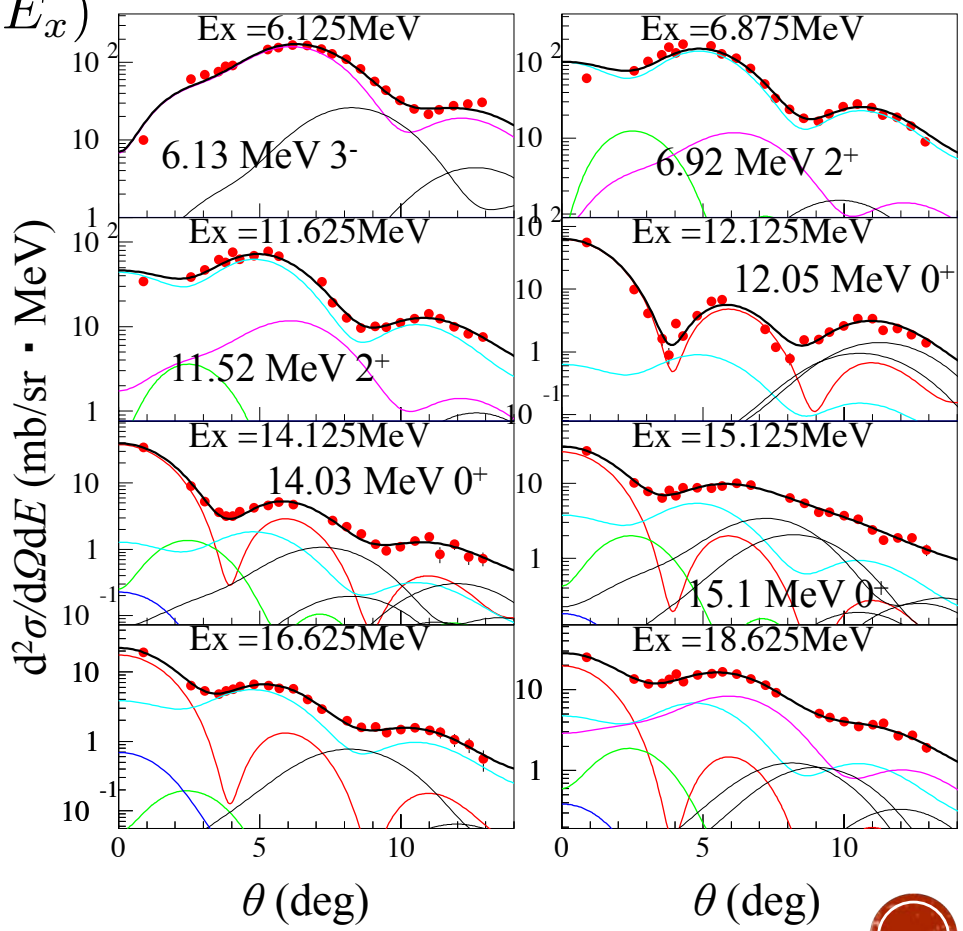


Result of the MDA in $^{16}O(\alpha,\alpha')$

- The Multipole Decomposition Analysis (MDA)

$$\frac{d\sigma^{exp}}{d\Omega dE}(\theta, E_x) = \sum_L a_L(E_x)\frac{d\sigma_L^{calc}}{d\Omega dE}(\theta, E_x)$$



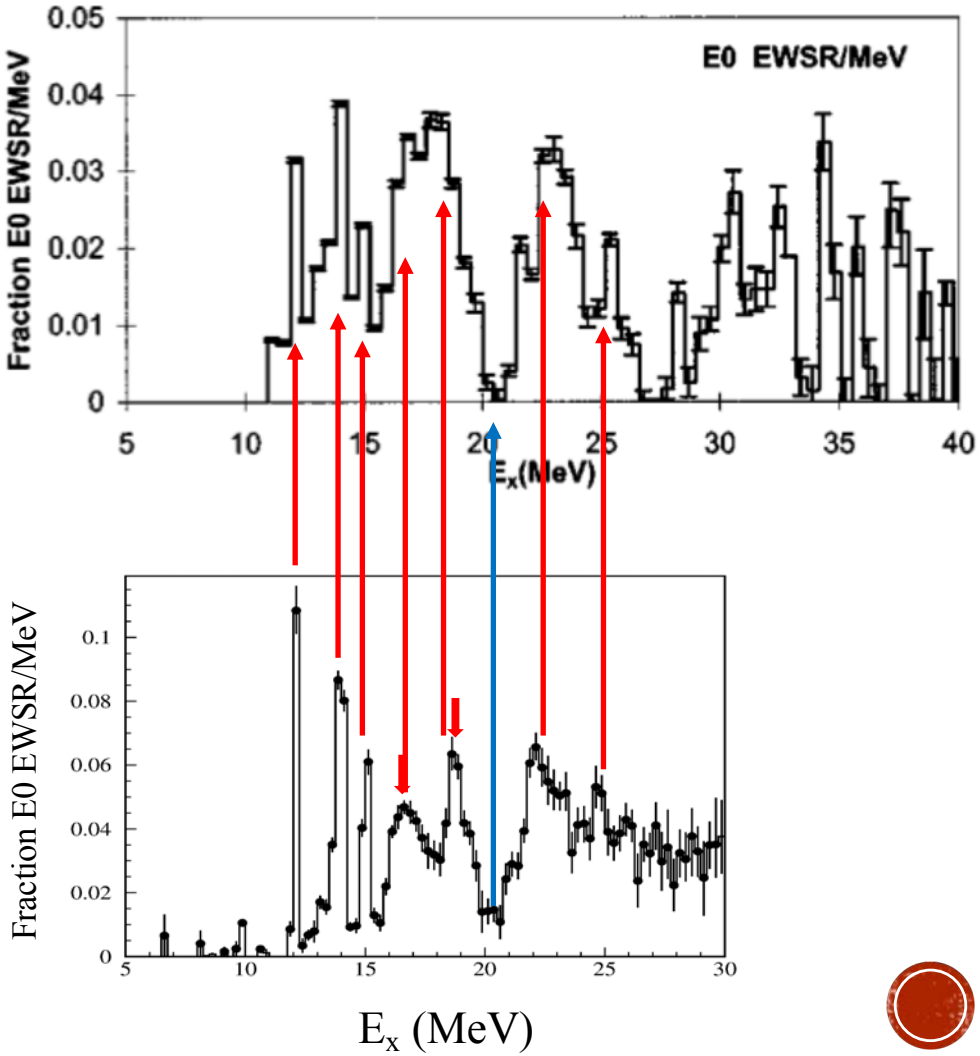


Isoscalar E0 Strength in ^{16}O obtained from the (α,α') experiment

- E_α=240MeV@TexasA&M
  Y.-W.Lui, H.L.Clark, and D.H.Youngblood, Phys.Rev.C 64 (20019)064308

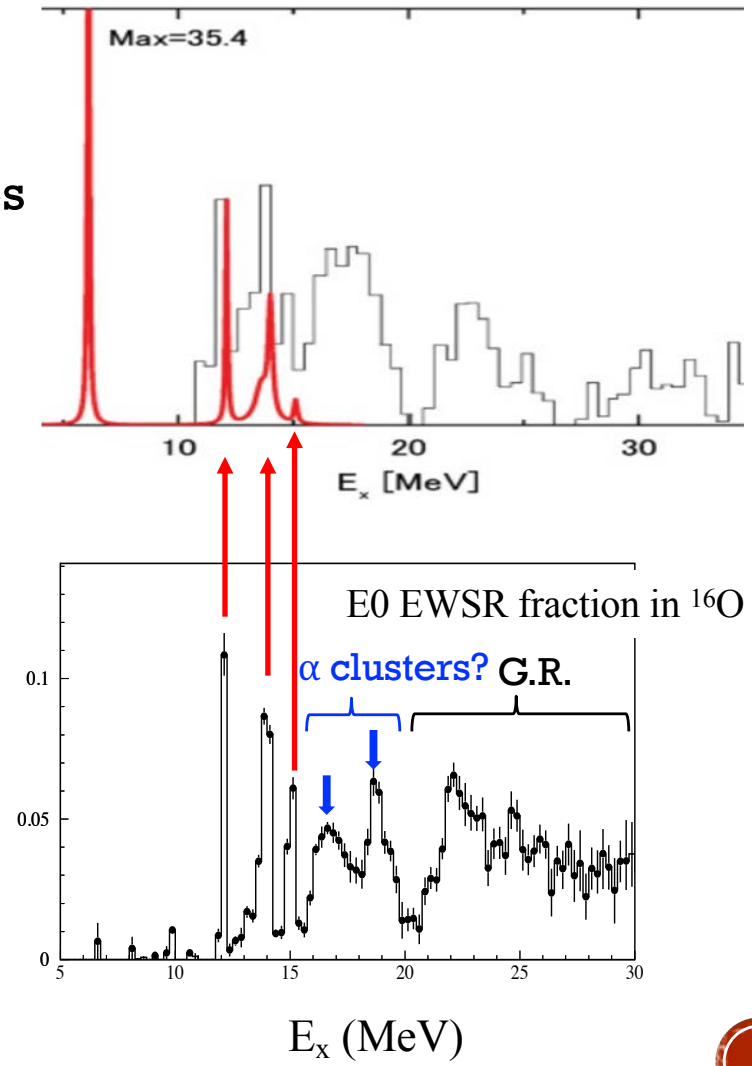
- E_α=386MeV@RCNP
  - Roughly same as TexasA&M
  - Two 0^+ resonances appear at 16.7 and 18.8 MeV

MI *et al*, J.Phys.Conf.Seri.569(2014)012009



Isoscalar monopole excitaion to α-cluster states in ^{16}O

- Isoscalar monopole excitations
  Y.Yamada et al,Phys.Rev.C85,034315(2012)
  - Monopole excitations to α-cluster states
    Ex ≦ 16 MeV, EWSR fraction ～ 20%
  - ISGMR (Ex > 16 MeV)

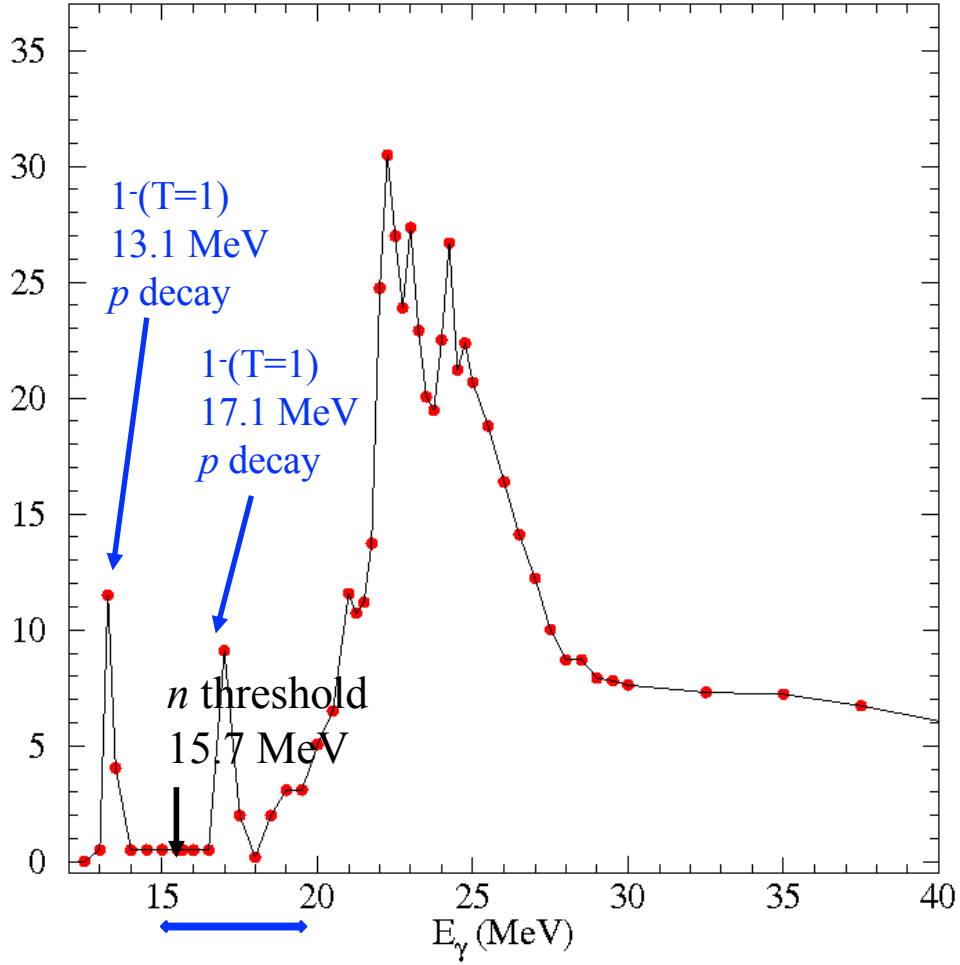


- Eα=386MeV@RCNP
  - E0 EWSR: 13% (8~16MeV)
  - 16 ≦ Ex ≦ 21 MeV
    Two 0^+ states:
    16.7MeV, 18.8 MeV
    → α-cluster states?

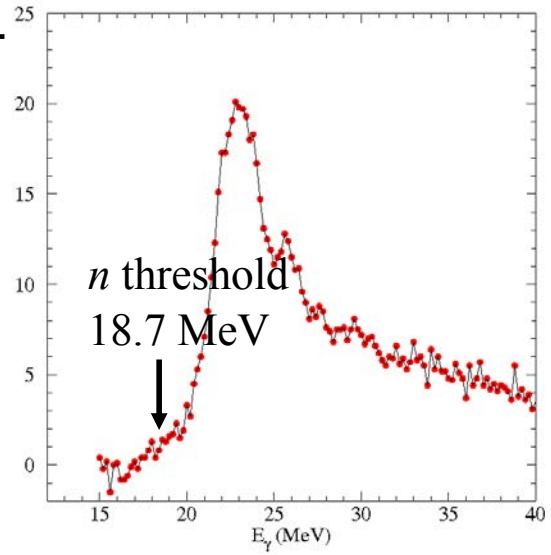
γ absorption cross section and Neutron threshold energy

- Neutron threshold energy of ^{16}O: 15.7 MeV

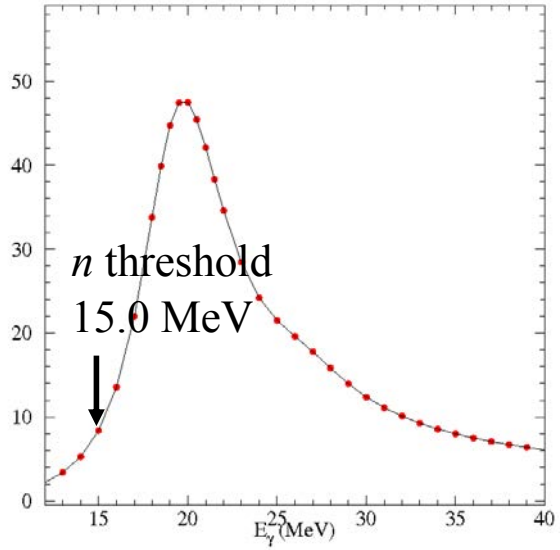
^{16}O γ absorption cross section



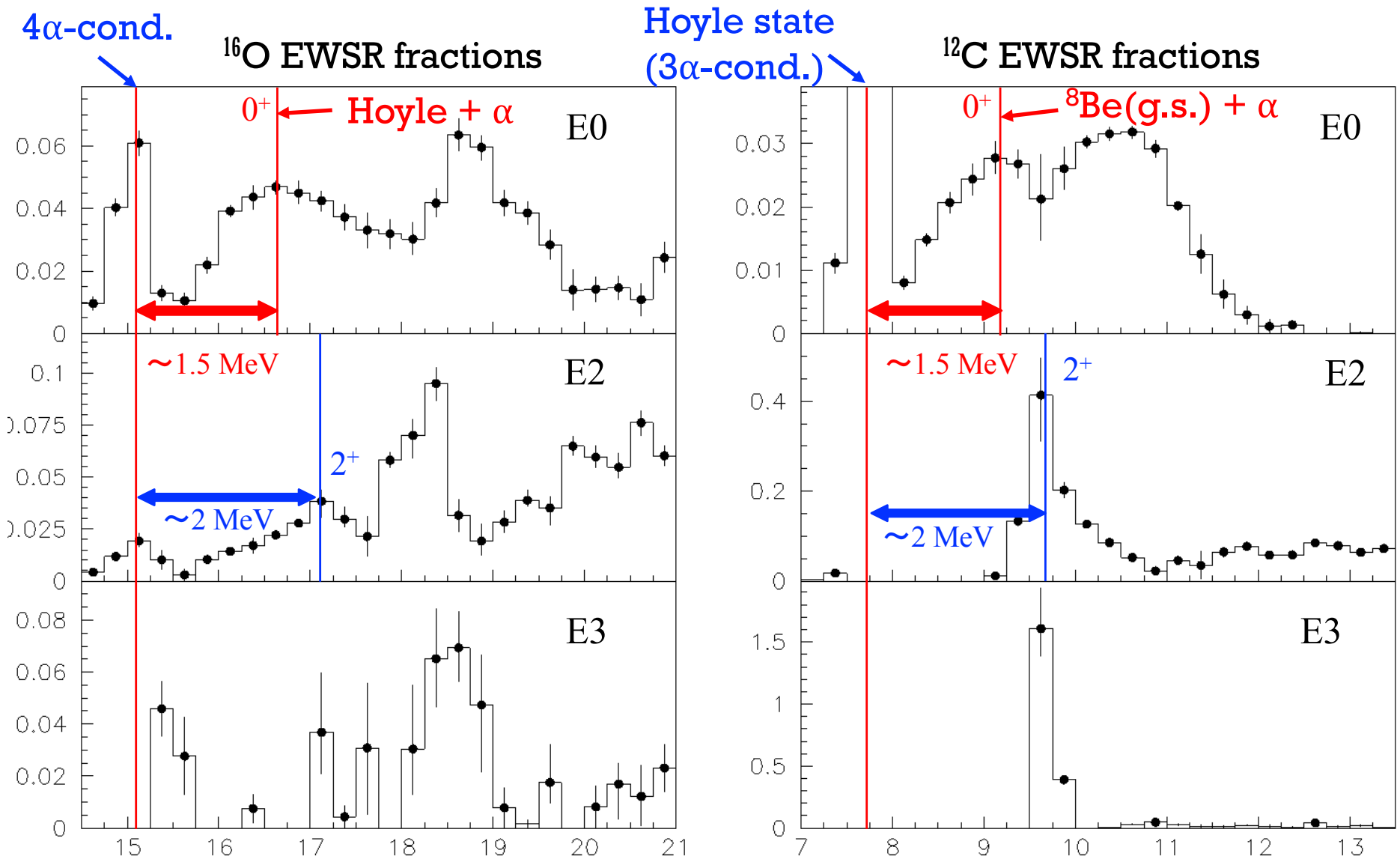
^{12}C γ absorption cross section



^{32}S γ absorption cross section



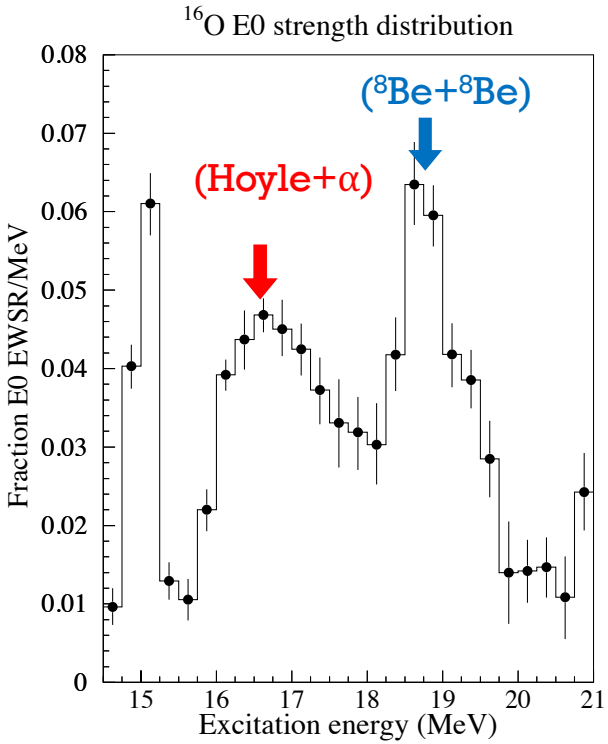
Analogy with the Ex ~ 10 MeV region in ^{12}C



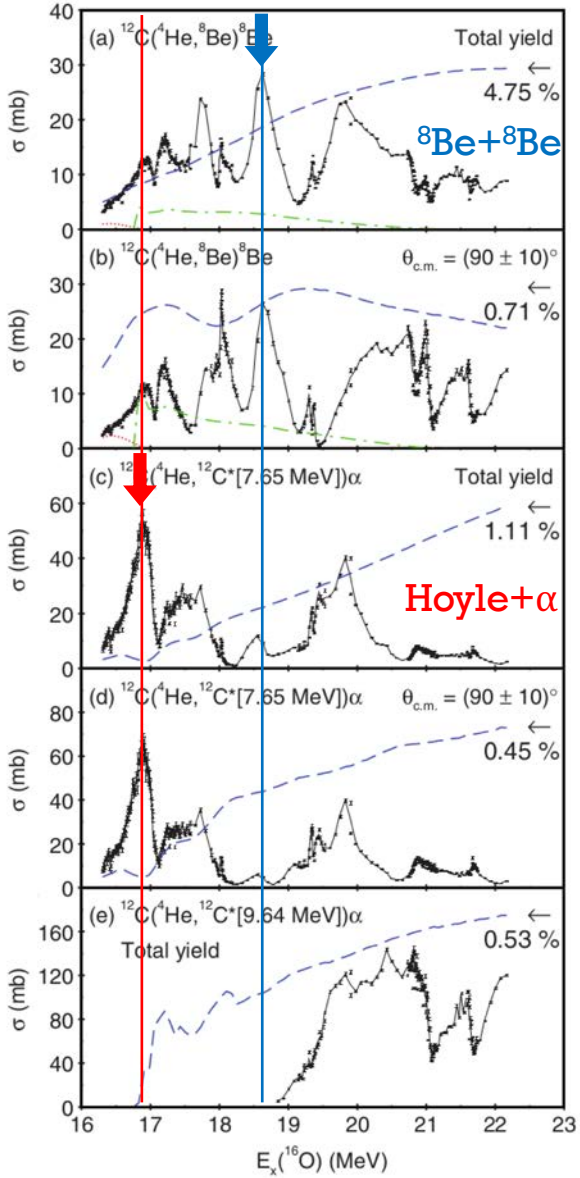
Comparison with the resonance scattering experiment

- 16.7 MeV 0^+: Hoyle + α
- 18.8 MeV 0^+: ^{8}Be + ^{8}Be

RCNP Exp.



MI *et al*,
J.Phys.Conf.Seri.569(2014)012009



N.Curtis *et al*,
PRC88,064309(2013)

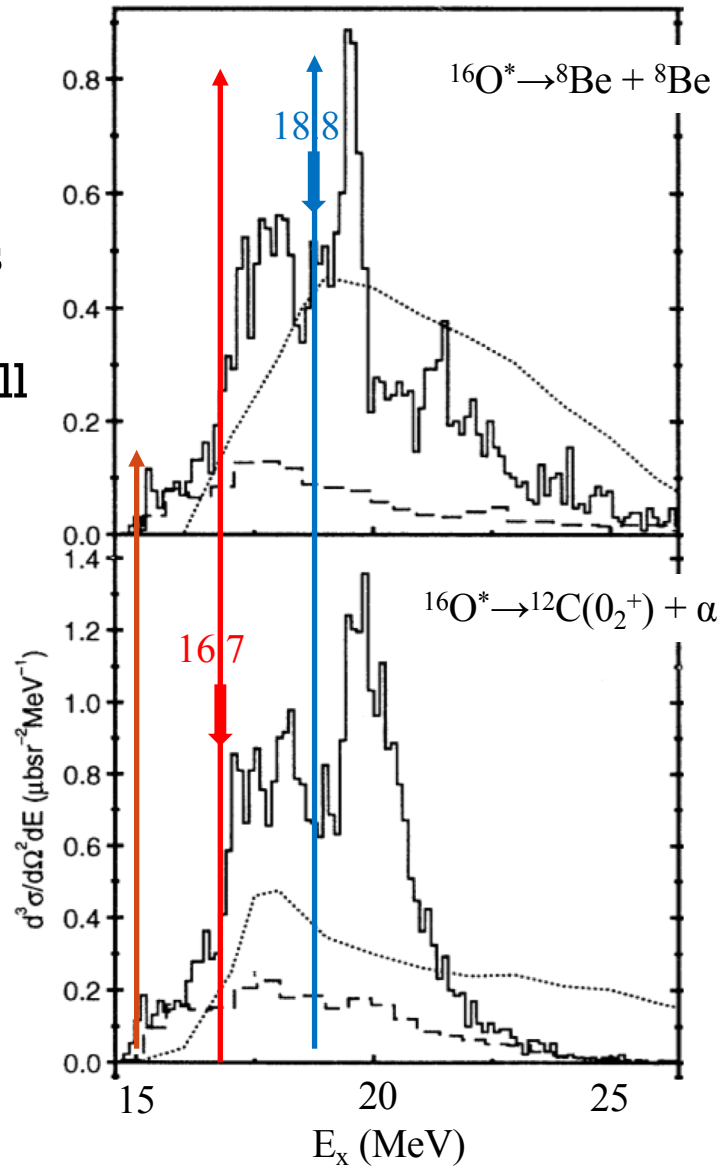
Motivation

- In order to investigate the properties of these two 0^+ states further, we measure decay-α particles from these two 0^+ states using the $^{12}C(^{16}O,4\alpha)$ reaction.
- We assume
  - the decay of the cluster state has a relatively high ratio of the decay into its cluster components.
  - $^{16}O^*$ (Hoyle + α cluster) $\rightarrow$ Hoyle + $\alpha \rightarrow 4\alpha$
  - $^{16}O^*$ (^8Be + ^8Be cluster) $\rightarrow$ ^8Be + $^8Be \rightarrow 4\alpha$
- Using the kinematical condition, we identify decay channels, Hoyle + α and ^8Be + ^8Be decay channels.

Previous experiments

- M.Freer *et al*, Phys.Rev.C51,1682(1995)
  - $^{12}C(^{16}O,4\alpha)$ reaction
  - They measured at backward angles (over 13°)
  - Contributions of 0^+ states were small

- Measurement angles from 1° to 14° (less than 14°)



^{20}Ne + α reaction experiment @ TexasA&M

- Thick target inverse kinematics (TTIK) method
  M.Barbui et al,PRC98,044601(2018)

^{4}He gas
4950 mbar

^{20}Ne beam
12MeV/nucleon

Measured multiple α decay events

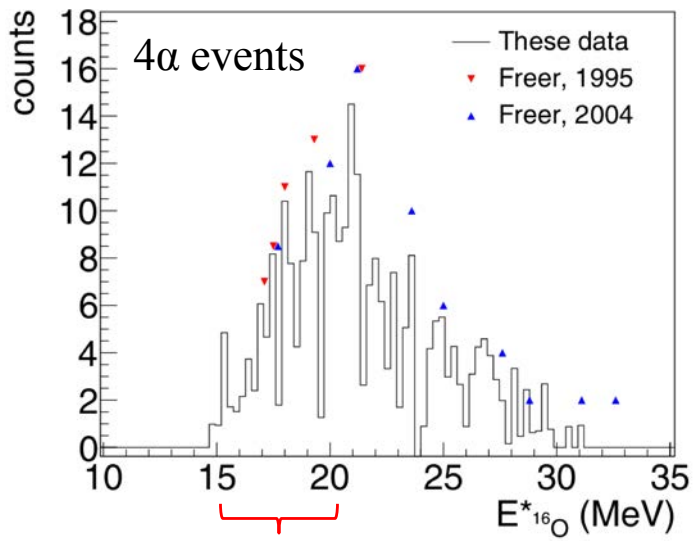


TABLE I. Relative partial decay widths.

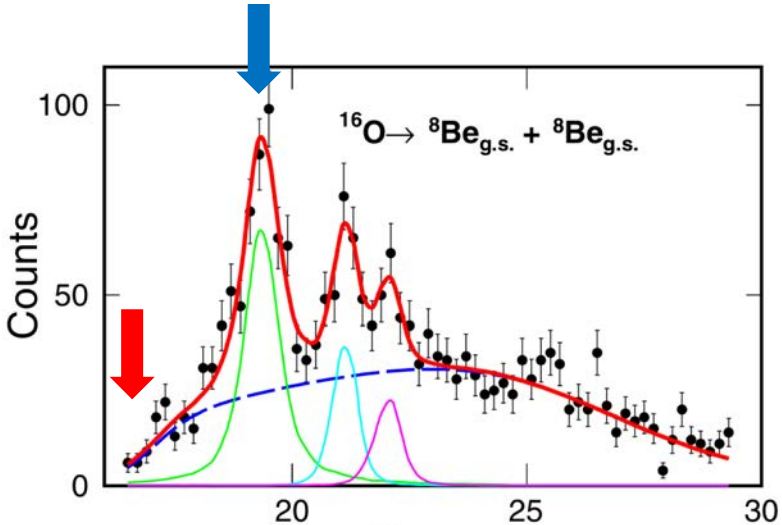
Energy	Γ(Be)/ Γ(Hoyle) This work	Γ(Be)/ Γ(Hoyle) Our previous work [23]	Γ(Be)/ Γ(Hoyle) Freer *et al.* [14]
15.2 ± 0.2	1 ± 0.7	0.96 ± 0.3	
17.1	0.6 ± 0.3	0.7 ± 0.3	0.65 ± 0.16
17.5		0.6 ± 0.3	0.72 ± 0.18
19.7	0.43 ± 0.2	0.6 ± 0.5	0.47 ± 0.15
21.4	5.3 ± 2.8	3 ± 1	>3 ± 1.1

Neutron-transfer reactions @ MSU

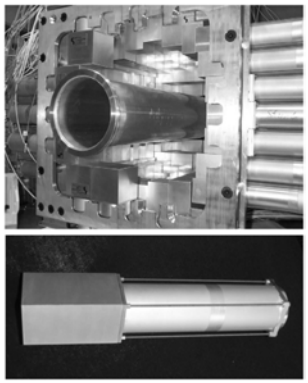
- The $^{9}Be(^{15}O,^{16}O^{*})^{8}Be$ reaction at E/A = 48.1 MeV/nucleon
  R.J.Charity et al, PRC99,044304(2019)

Ex ~ 16.7 MeV

Ex ~ 18.8 MeV

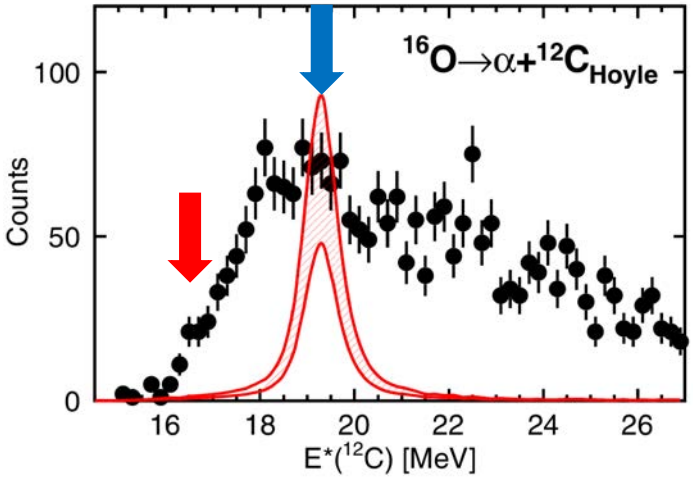


HiRA covered zenith angles
from 2° to 13.9°
M.S.Wallace et al,NIMA583,302(2007)



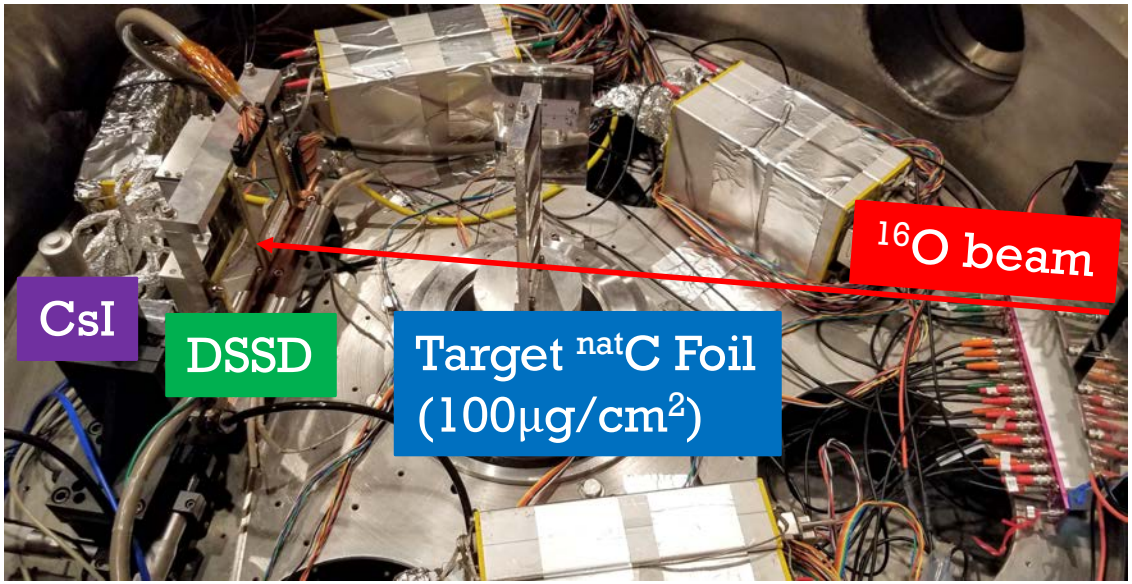
CAESAR
for γ detections

D.Weisshaar et al,
NIMA624,615(2010)



EXPERIMENT @ CYRIC

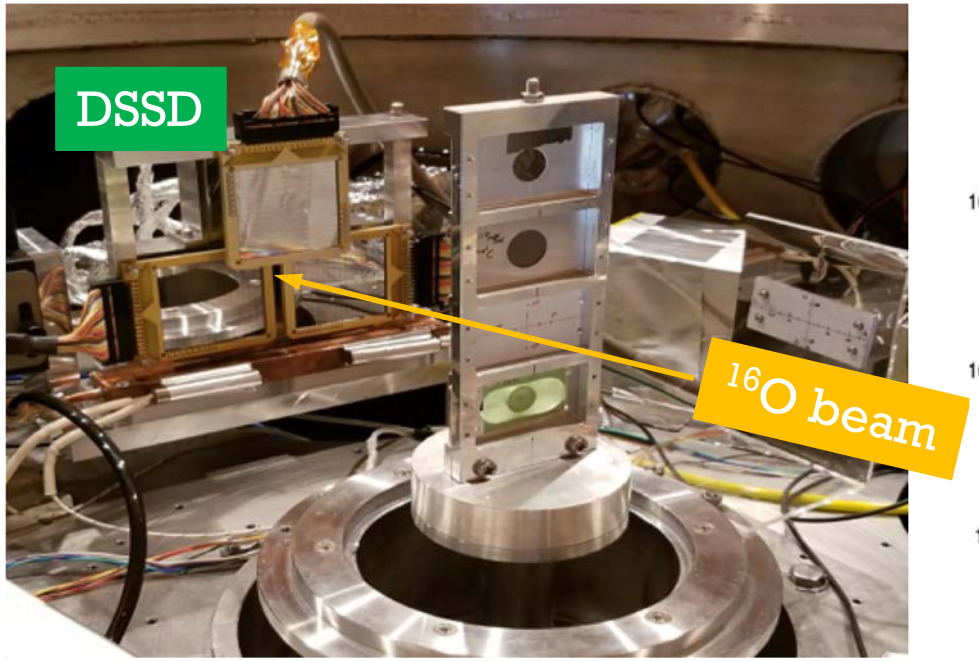
- Facility: CYclotron and RadioIsotope Center (CYRIC) in Tohoku University
- $^{12}C(^{16}O,^{16}O^*[4\alpha])^{12}C$ reaction at $E(^{16}O) = 160$ MeV
- DSSD: Double-sided Silicon Strip Detector(50×50 mm^2, 1500μm, 3 mm strip) × 3
- CsI: CsI detectors (25×25×25mm^3) × 12

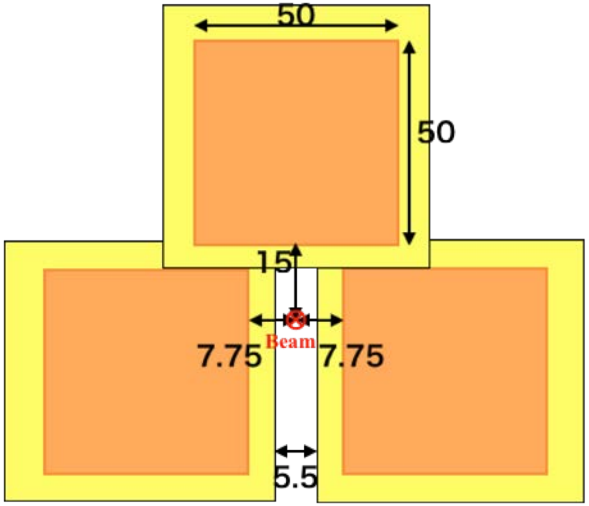


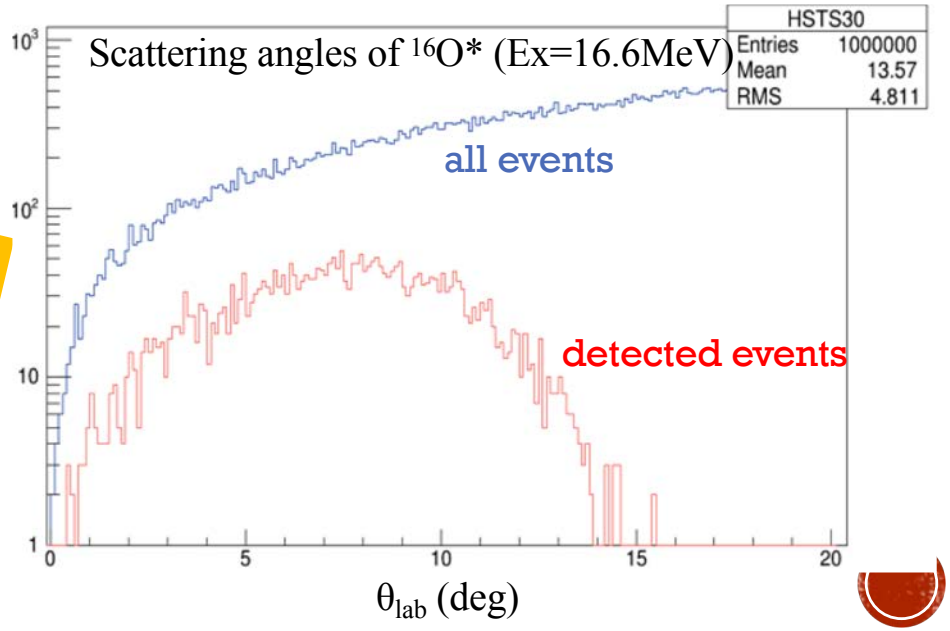
AVF Cyclotron @ CYRIC

DETECTOR SET-UP

- DSSD:
  - Distance: 185mm from target
- Covered angles: 2.2°~17.7°
  - Scattering angles of $^{16}O^*$: 1°~13°

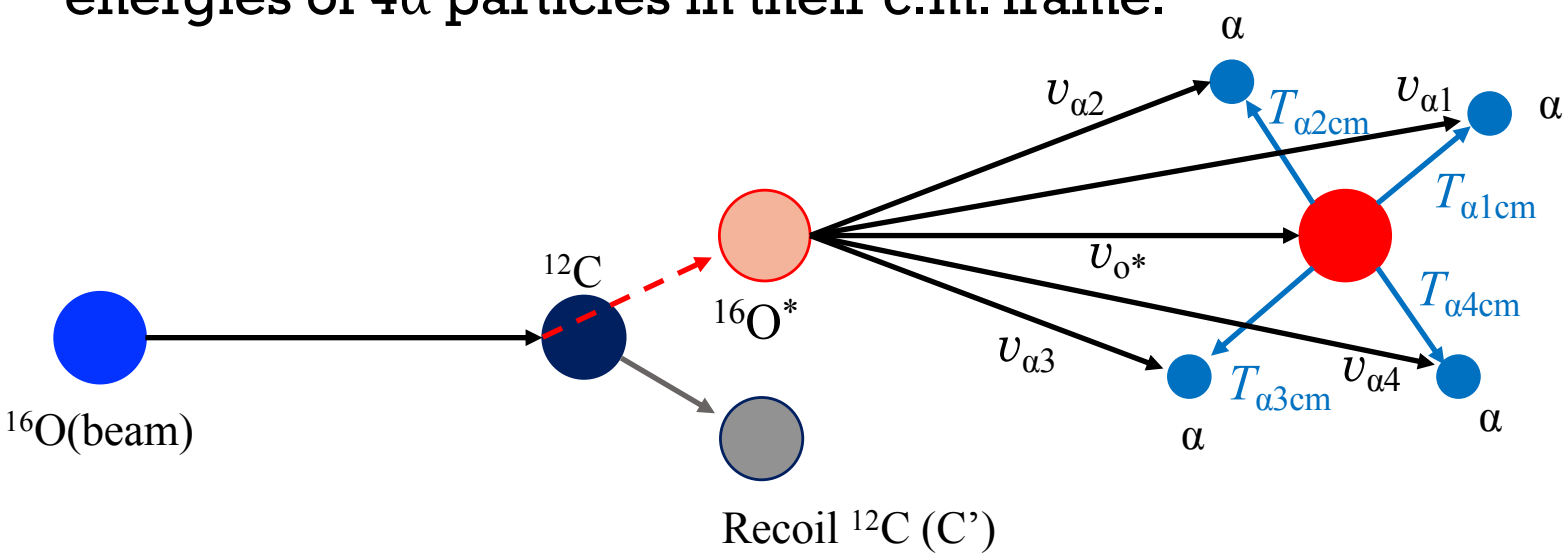






Excitation energy in ^{16}O

- Excitation energy was calculated from the sum of the kinetic energies of 4α particles in their c.m. frame.



$$T_{beam} = \sum T_{\alpha_i} + T_{C'} + 4m_\alpha - m_O$$

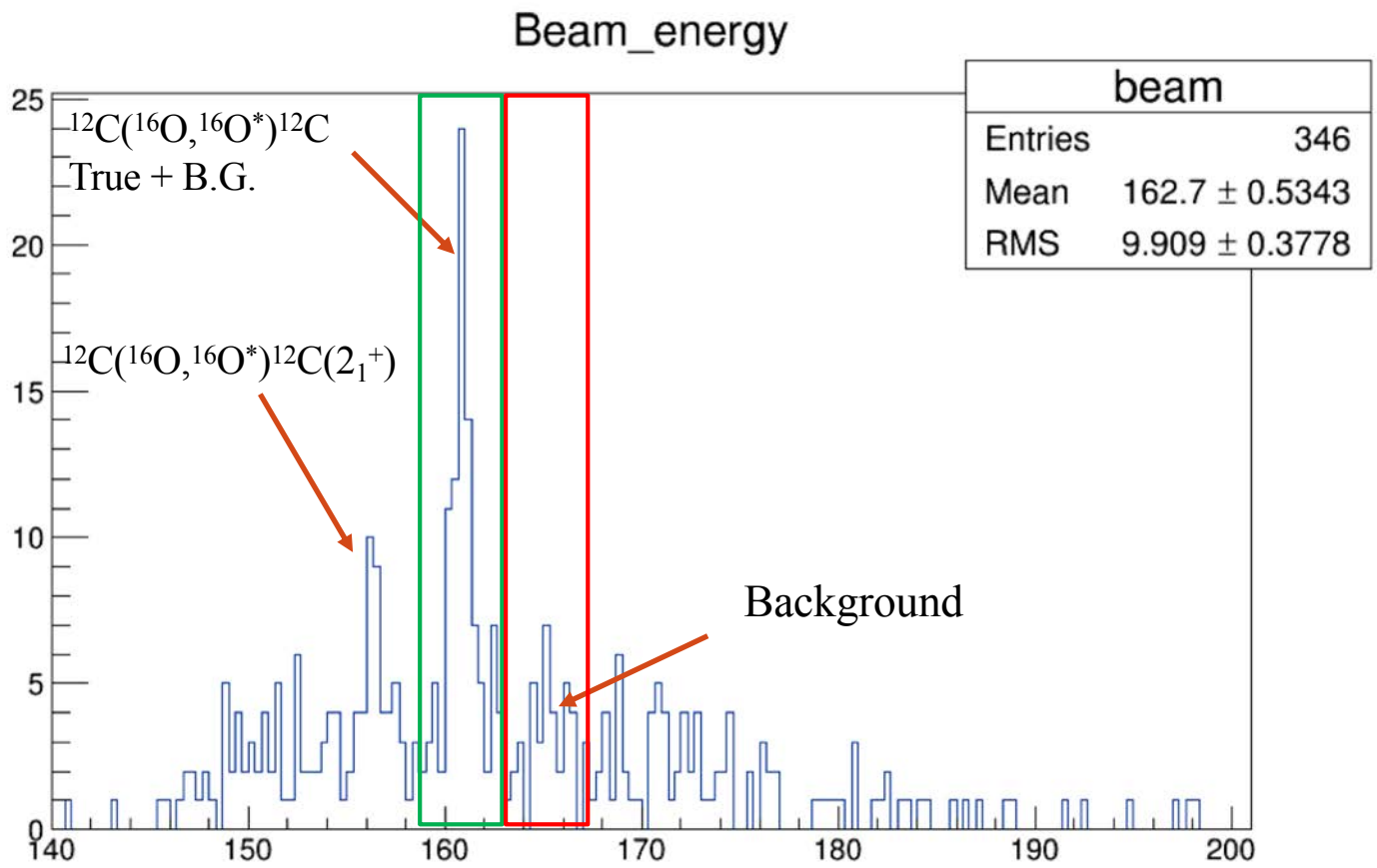
$T_{C'}$: calculate from vertical momentum of $^{16}O^*$

$$E_x = T_{\alpha_1 cm} + T_{\alpha_2 cm} + T_{\alpha_3 cm} + T_{\alpha_4 cm} + 4m_\alpha - m_O$$

Invariant mass method

Reconstructed Beam energy

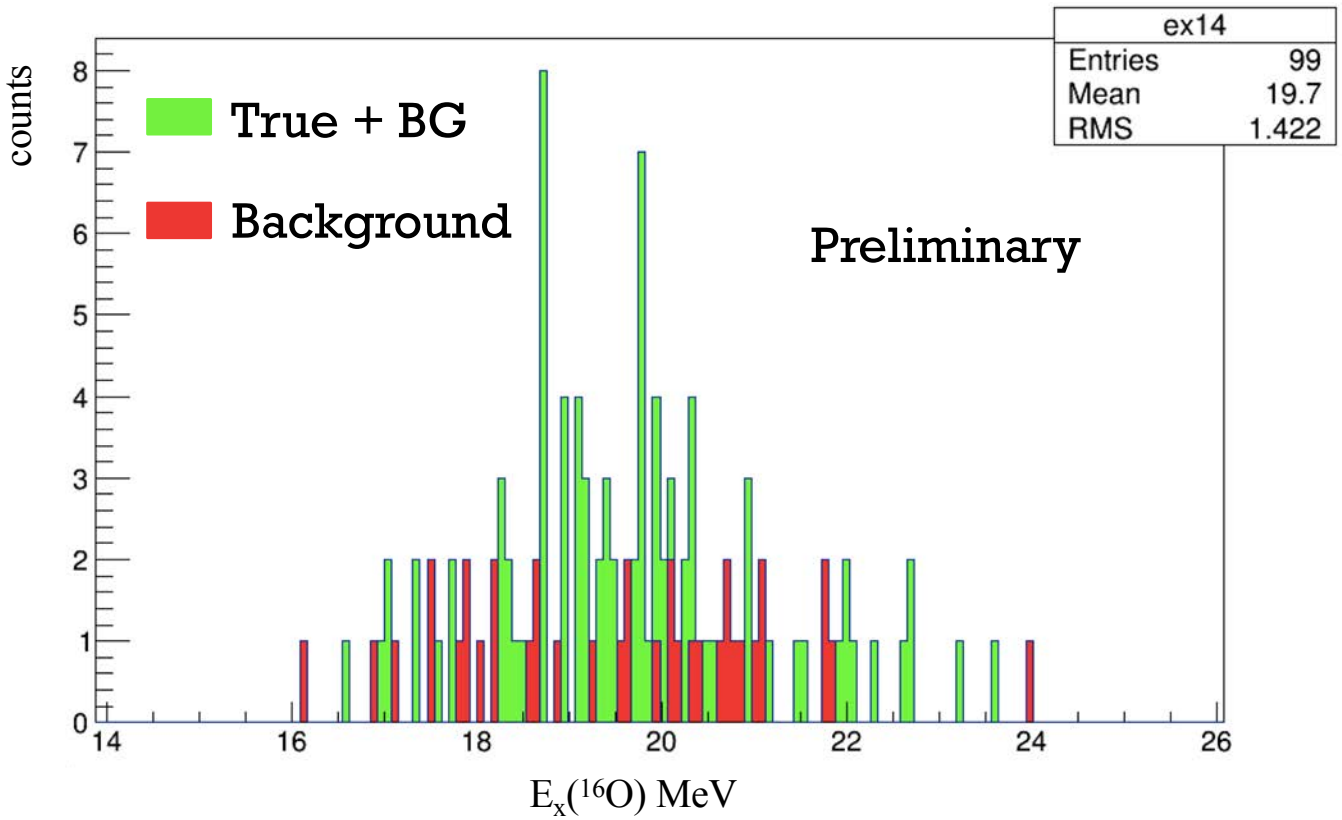
- Energy conservation law: $T_{beam} = \sum T_{\alpha_i} + T_{C'} + 4m_\alpha - m_O$



Excitation energy spectrum in ^{16}O

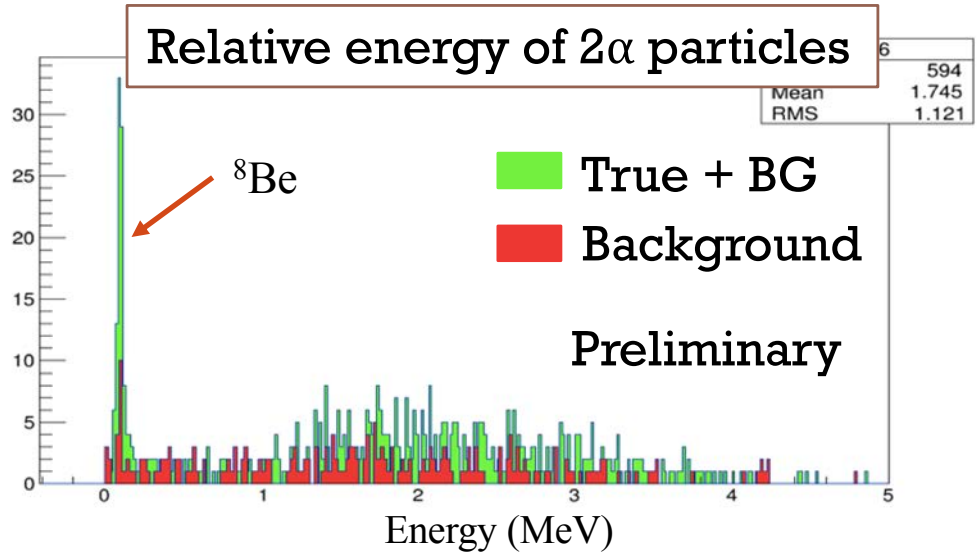
- The excitation energy spectrum in ^{16}O can be reconstructed from 4α decay channels.

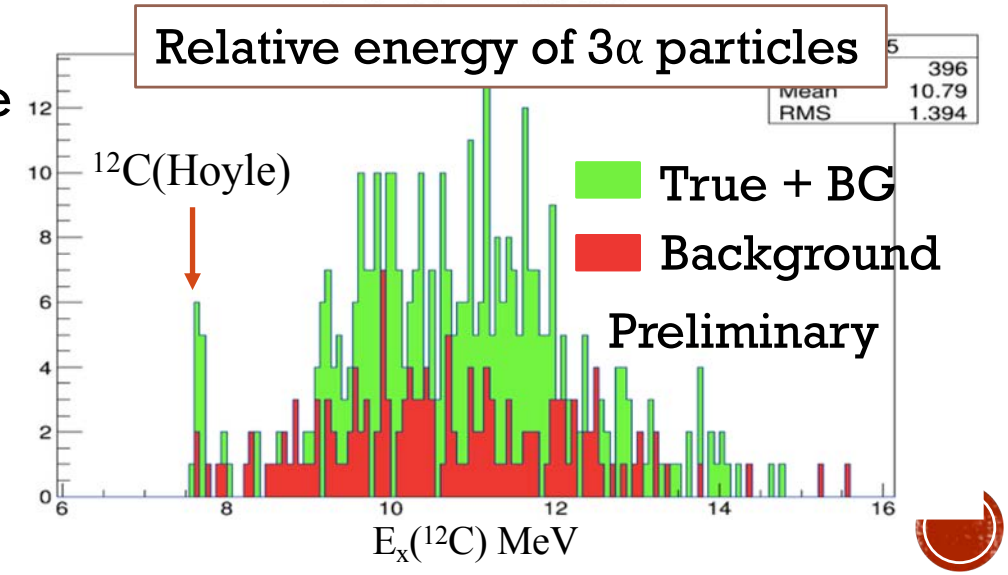
$$E_x = T_{\alpha_1 cm} + T_{\alpha_2 cm} + T_{\alpha_3 cm} + T_{\alpha_4 cm} + 4m_\alpha - m_O$$



Relative energy spectra for break-up 2α and 3α particles

- Relative energy of 2α particles
- Relative energy of 3α paritcles
- The ground state of ^{8}Be decay channel and the 0_2^+ (Hoyle) state of ^{12}C decay channel were able to be measured, clearly.
- Statistics are very low…
- We plan to do the same experiment to collect larger statistics data.





SUMMARY

- α gas-like states near the four α threshold energy in ^{16}O have been studied by inelastic α scattering of ^{16}O and the measurement of 4α decays in the $^{16}O + {}^{12}C$ reaction.

- Two candidates for α gas-like states have been found at Ex = 16.7 MeV and Ex = 18.8 MeV by the MDA of inelastic α scattering.

- The measurement of 4α decays in the $^{16}O + {}^{12}C$ reaction has been launched. In order to collect high statistics, we plan to do experiment, again.

COLLABORATORS

- Cyclotron and Radioisotope Center, Tohoku University
  - MATSUDA Yohei
  - ISHIBASHI Yoko
  - ISHIDA Shunya
  - NAKAGAWA Anna
  - MAEDA Ryu
  - NOZAWA Katsuaki

Thank you for your attention.